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The Role of Robots and Automation in Space

Ewald Heer

September 1, 1978

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

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ABSTRACT

Advanced space transportation systems based on the Shuttle and Interim Upper Stage will open the way to the use of large-scale industrial and commercial systems in space. The role of robot and automation technology in the cost-effective implementation and operation of such systems in the next two decades is discussed. Planning studies initiated by NASA are described as applied to space exploration, global services, and space industrialization, and a forecast of potential missions in each category is presented. The Appendix lists highlights of space robot technology from 1967 to the present.

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SECTION I

INTRODUCTION

The space program is at the threshold of a new era that is distinguished by a highly capable space transportation system. In the 1980s, the Space Shuttle and Interim Upper Stage will enable increased activities in the scientific exploration of the universe and a broadened approach to global service undertakings in space. The first steps towards utilizing the space environment for industrial and commercial ventures will become possible and can trigger requirements for more advanced space transportation systems in the 1990s. This will enable expanded space industrial activities and, by the end of this century, could lead to Satellite Power Systems for solar energy production, to lunar bases for extracting and processing material resources, and to manned space stations for commercial processing and manufacturing in space. A major objective for NASA is to develop the enabling technology and to reduce the costs for operating such large-scale systems during the next two decades. On examining potential NASA missions in this time frame, it is expected that robot and automation technology will be a vital contributor to the cost-effective implementation and operation of the required systems. In some areas it will make the system feasible, not only for technological reasons but also in terms of commercial acceptability and affordability.

The term robot means here a general-purpose system with a great degree of autonomy. By means of a computer as the central element, the robot is able to sense its environment, plan and decide its actions, and perform mechanical manipulations and data handling tasks sometimes to a degree normally done by humans. Automation, on the other hand, has the usual connotation of self-acting and self-regulating machinery performing specialized preprogrammed tasks. While in the business world the words automation and computers are often used synonymously, in manufacturing the use of computers as the central element in automated systems is only now becoming dominant. Because of the central role of computers in many space systems, both robotics and automation have pervaded the space program, at least to some degree, in many guises since its inception. However, these trends did not take sufficient advantage of the technological developments during the last one or two decades. Some have criticized NASA for this, stating that the computer technology used in NASA missions is at least 10 years behind the times. While some of the criticisms are not justified, some may be valid. The valid ones can usually be traced back to the generally accepted requirement of flawless performance of NASA missions (often for political reasons) and to long lead times from project conception to implementation. Projects and missions are usually conceived and their objectives defined based on then proven technology rather than on the technology existing at the time of the project design period.

During the next two decades, the space program will shift emphasis from exploration to exploitation of the space environment. It is expected that this shift will be accompanied by a large increase in requirements for system operations in space and on the ground, calling for general-purpose automation (robotics) and specialized automation. The question that must be asked (and answered) is: What operations, tasks, and functions must be automated, and to what degree, to accomplish the NASA objectives with the most cost-effective systems? After answering this question, it will be possible to derive the required technologies and to define development plans. Rather than leaving the development of technology to an evolutionary process, it will then be possible to take objective-oriented action.

Looking back on industrial evolution, there are a number of key steps: division of labor, use of mechanical power, standardized parts, transfer devices, open-loop control, closed-loop control, and computer control. These steps indicate a progression in the amplification of human capabilities. Until the dawn of the industrial revolution, human physical capabilities (muscle power) were amplified through the use of simple machines. Then, automation also came into the picture. After a slow beginning, automation has been moving on with ever-increasing pace, helping to accomplish more and more human tasks. By means of limit switches and governors, the machine became able to make simple decisions on its own, such as "go-stop" or "more-less." Some outstanding examples are assembly line transfer devices in automobile manufacturing during the early twentieth century, systems with open-loop mechanical control around World War I, and systems with closed-loop control approximately during World War II.

In the 1940s, the advent of the digital computer also opened up the possibility of performing many so-called low-level (and possibly high-level) intellectual activities automatically. In addition to the long-standing amplification of human physical capabilities, the amplification of the human mind was in the making.

Since the first commercial computers were introduced in the early 1950s, the "electronic brain" has brought widespread changes. It has reached into innumerable crevices of our lives. At last count, some 1800 firms and more than 4% of our labor force were dedicated to maintaining and extending automation through computers. Today computer-automated operations include collecting, maintaining, and assimilating enormous amounts of data. Automatons greatly simplify operations and reduce costs. They pay bills and keep track of accounts, inventories, personnel, and pricing. In factories, many routine or dangerous tasks are done by computer-controlled manipulators. Even some engineering design and analysis are done automatically.

Not counting the hundreds of thousands of microprocessors proliferating in our society, we have today almost 200,000 free-standing computers. If one added up the performance of these machines in terms of their human equivalent, one would find that it would take more than

400 billion people to accomplish the same tasks that these machines perform today. Considering that, conservatively, at most 20% of the U.S. population is engaged in relevant work using these computers, we have built into our society a mind-amplifying factor of about four orders of magnitude. Clearly America already depends on automated machines so much that the country, including the space program, would come to a grinding halt without them. The man-machine symbiotic existence is here, and this relationship is moving with ever increasing speed in the direction of more automation.

Developments in automation are paced by the rapidly advancing electronics and computer technology projected in Figures 1-4 (Ref.1). No end of potential accomplishments are in sight, and ongoing research only hints at what the future might offer.

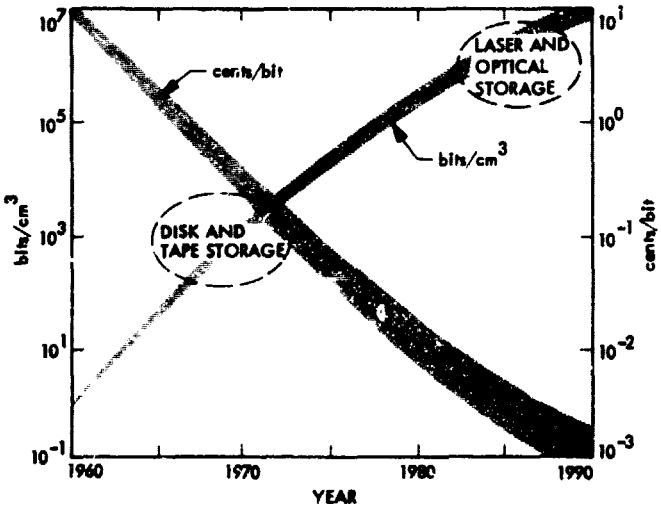


Figure 1. Data storage technology. The storage capacity is doubling every 1 1/2 years, while the cost of random access memory is halving every 2 1/2 years. In 1960, the equivalent of 1 m^3 stored a 15-page pamphlet; in 1980, the same space will accommodate a 2000-book library and in 1990, the entire Library of Congress.

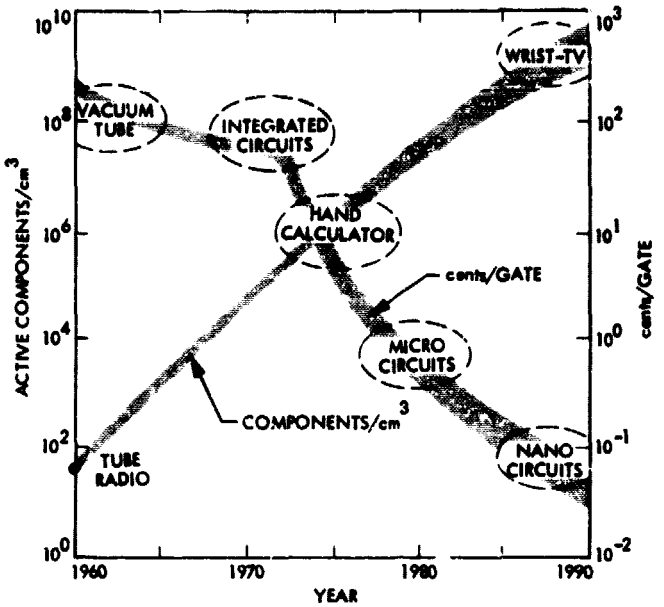


Figure 2. Active devices technology. The number of active components per cubic centimeter is doubling every 1 1/8 years, while the average cost per logic gate is halving every 2 1/2 years.

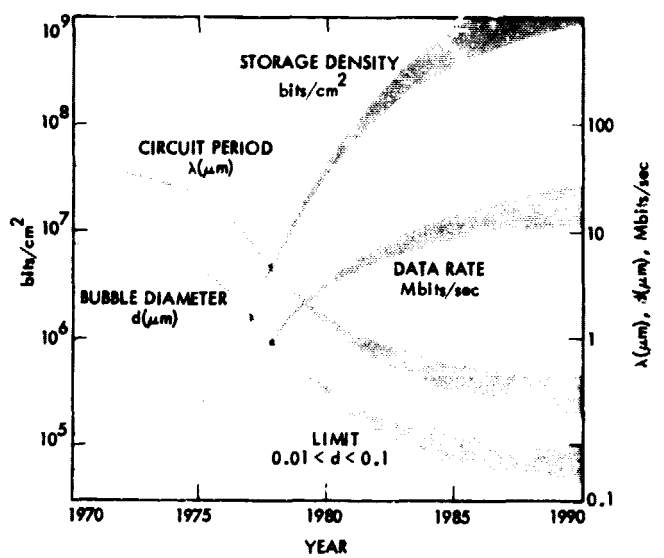


Figure 3. Bubble memory technology. About 4×10^8 bits/cm^2 would be reached in 1985. This implies a bubble diameter of 10^{-5} cm, which is ten times greater than the theoretical limit. (Adapted from A.H. Bobeck, Bell Laboratory, ELECTRO '77, N.Y.).

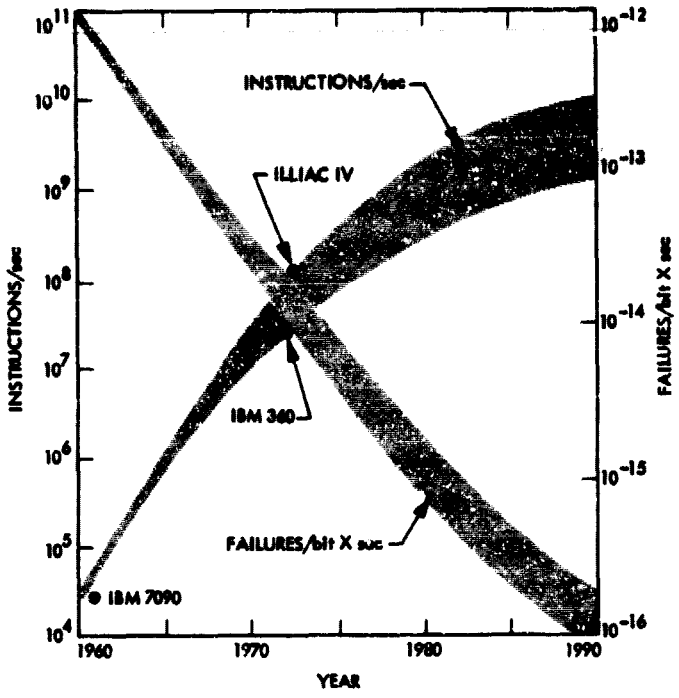


Figure 4. Computer systems technology. The average increase of computer speed is doubling every 1 1/2 years, while the failure rate is halving every 2 3/4 years.

SECTION II

ROBOTS AND AUTOMATION IN NASA PLANNING

While mechanical power provides physical amplification and computers provide mind amplification, telecommunication provides space amplification, i.e., amplification of the space accessible to humans. By means of telecommunication, humans can activate and control systems at remote places. They can perform tasks even as far away as the planets. During the 1960s, this became known as teleoperation (Refs. 2-4). Teleoperators are defined as general-purpose, remotely controlled, cybernetic, dexterous man-machine systems that augment and extend human sensory, manipulative, and cognitive abilities to remote places (Ref. 5). In this context, the term robot can then be applied to the remote system of a teleoperator if it has at least some degree of autonomous sensing, decision-making, and action capability. The concept of teleoperation has profound significance in the space program. Because of the large distances involved, almost all space missions fall within the teleoperator definition, and because of the resultant communication delay for many missions, the remote system requires autonomous capabilities for effective operation (Ref. 6). The savings of operations time for deep space missions can become tremendous if the remote system is able to accomplish its tasks with minimum ground support. For example, it has been estimated that a Mars roving vehicle would be operative only 4% of the time in a so-called move-and-wait mode of operation. With adequate robot technology, it should be operative at least 80% of the time.

The ability of a robot to act independently from human operators is provided by its computer brain. The brain, consisting of computer hardware and software, incorporates the robot's intelligence, i.e., machine intelligence. By this is meant something slightly different from artificial intelligence (AI), which has been characterized in many but similar ways by workers in the field (Refs. 7 and 8) This writer likes to call artificial intelligence the study of intellectual activities using computers. In this sense, AI is thought of as a collection of scientific research themes devoted to problem solving, scene analysis, theorem proving, speech understanding, and the like. Understanding the processes associated with these themes, and simulating them on electronic computers, is fundamental to the development of machine intelligence technology.

The Appendix highlights chronologically some of NASA's space robot technology planning, development, and application activities during the last decade. The References contain an extensive bibliography related to NASA and non-NASA activities in the areas of robotics, automation, and teleoperation. It is clear that the issues associated with these areas are interdisciplinary and complex. They involve not only technological considerations on the broadest scale but also assessments of economic feasibility and affordability.

NASA saw the need to examine the civilian role of the U.S. space program during the last quarter of this century. A series of planning studies and workshops was initiated with the Outlook for Space Study in 1974 (Ref. 9), which included a comprehensive forecast of space technology for 1980-2000. In a subsequent NASA/OAST Space Theme Workshop (Ref. 10), the technology forecasts were applied to three broad mission themes: space exploration, global services, and space industrialization. Based on the derived requirements for cost-effective space mission operations, Kurzhals (Ref. 11) identified five new directions for space electronics technology developments: (1) automated operations aimed at a tenfold reduction in mission support costs; (2) precision pointing and control; (3) efficient data acquisition to permit a tenfold increase in information collection needed for global coverage; (4) real-time data management; and (5) low-cost data distribution to allow a thousandfold increase in information availability and space-systems effectiveness. The machine intelligence and automation technologies for data acquisition, data processing, information extraction and decision making emerge here as the major drivers in each area and call for the systematic exploitation of the spectacular developments in electronics. In addition, for certain areas such as automated operations in space, the mechanical technologies directed at materials and objects acquisition, handling, and assembly must also be further developed; robots doing construction work in Earth orbit or on the lunar surface will need manipulative and locomotion devices to perform the necessary transport and handling operations.

SECTION III

FUTURE APPLICATIONS

In space applications, robots may take on many forms. None looks like the popular science fiction conception of a mechanical man. Their appearance follows strictly functional lines, satisfying the requirements of the mission objectives to be accomplished. Adopting the themes of the NASA/OAST Space Theme Workshop, the following lists briefly present mission categories. mission objectives, and system characteristics pertinent to space robot and automation technology and are related to Table 1.

(1) Missions for Space Exploration

(a) Galileo Jupiter orbiter probe releases an atmospheric probe into Jupiter and performs repeated close encounter maneuvers with the Galilean satellites.

(b) Solar Polar mission uses the gravity field of Jupiter to put the spacecraft into out-of-ecliptic solar orbit.

(c) Venus Orbital Imaging Radar maps the entire planet surface with high-data-rate Synthetic Aperture Radar

(d) Spacelab Instrument Program studies processes in the Earth-space milieu through multiuser instruments.

(e) X-Ray Observatory studies stellar and galactic phenomena from Earth orbit using broad-bandwidth x-ray.

(f) Saturn Orbiter Dual Probe releases an atmospheric probe at Saturn and an atmospheric probe-lander at Titan after repeated orbit maneuvers.

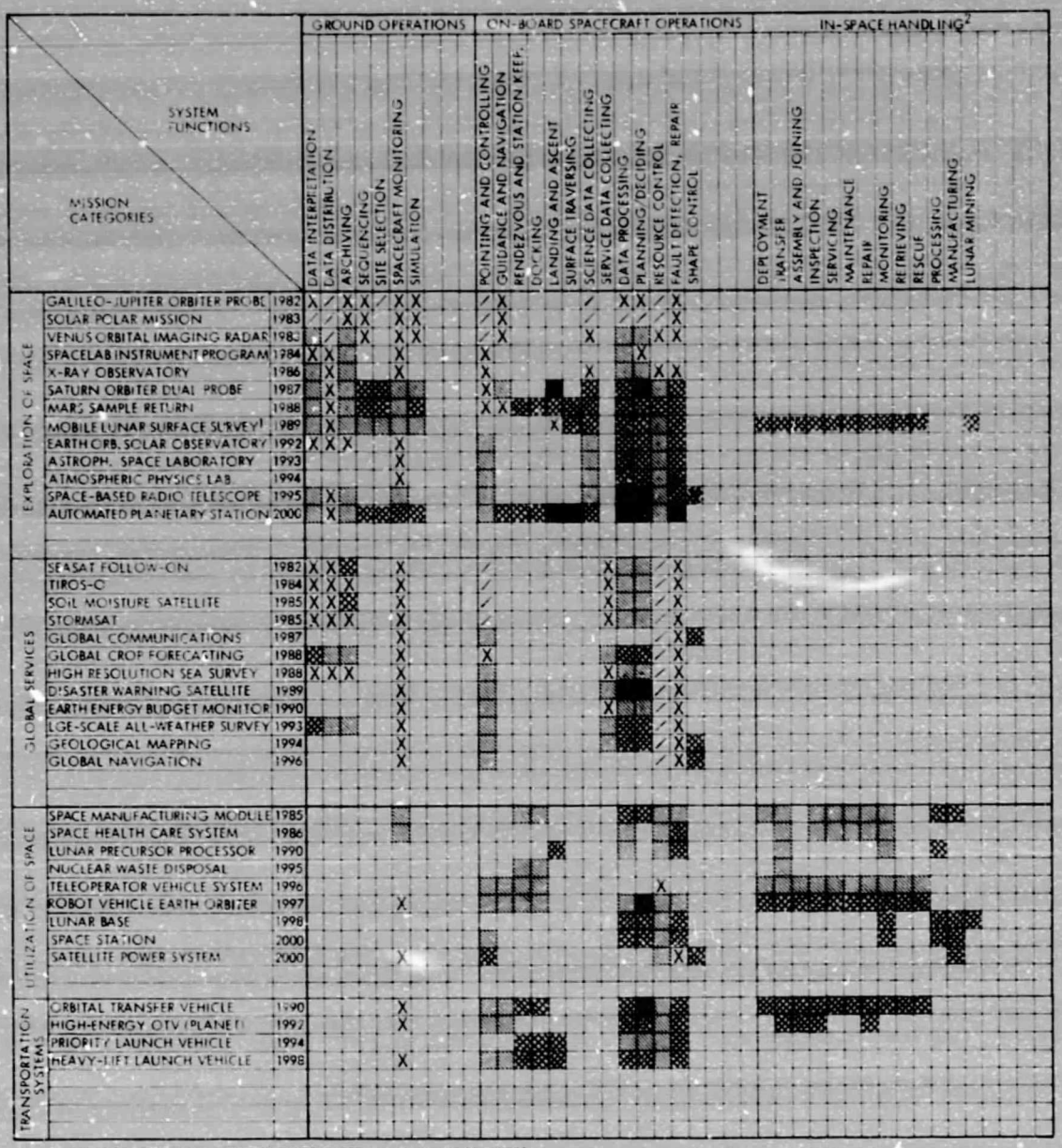
(g) Mars Sample Return includes orbiters; vehicles for descent, ascent, and return; penetrators; flyers; and surface rovers for intensive investigations.

(h) Mobile Lunar Surface Survey includes rovers for scientific investigations, prospecting for resources, and mining.

(i) Earth Orbital Solar Observatory provides long-duration solar observations from Earth orbit for detailed solar mapping.

(j) Astrophysics Space Laboratory in Earth orbit conducts extensive surveys of known or suspected objects in space.

Table 1. Estimates of technology development efforts to automate system functions



KEY: THE AUTOMATION OF THE IDENTIFIED SYSTEM FUNCTIONS REQUIRES

/ INTEGRATION OF EXISTING TECHNOLOGY

X MODERATE ADDITIONAL DEVELOPMENTS

EXTENSIVE TECHNOLOGY DEVELOPMENTS

MAJOR TECHNOLOGY DEVELOPMENTS

MAJOR TECHNOLOGY DEVELOPMENTS WITH UNCERTAIN OUTCOME.

NOTE: EACH ENTRY REPRESENTS THE RELATIVE COLLECTIVE LEVEL OF EFFORT REQUIRED TO ACCOMPLISH THE FUNCTION FOR THE MISSIONS AS DESCRIBED IN THE NASA OAST SPACE SYSTEMS TECHNOLOGY MODEL, 22 MARCH 1978.

[1] THE LUNAR ROVERS OF THIS PROGRAM WILL BE DEVELOPED WITH IN-SPACE HANDLING CAPABILITIES AND WILL SUPPORT THE LUNAR PRECURSOR PROCESSOR (1990) AND THE LUNAR BASE (1998).

[2] HANDLING FUNCTIONS ARE GENERALLY ASSOCIATED WITH MOBILITY UNITS, MANIPULATIVE DEVICES OR TOOLS REQUIRING CONTROL OF ACTUATORS

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(k) Atmospheric Physics Laboratory in Earth orbit conducts an extensive atmospheric research program to develop atmospheric models.

(l) Space-Based Radio Telescopes in Earth orbit are 200 to 3000-m-diameter reflector systems to study intergalactic phenomena.

(m) Automated Planetary Station is a large, highly automated spacecraft capable of conducting extensive scientific investigations anywhere in the solar system for extended periods of time. The spacecraft will have the capability to accommodate and control the operations of atmospheric entry probes, surface penetrators, mobile lander systems, mini-satellites, and sample return vehicles as required by individual mission objectives. The spacecraft will be capable of operating at least 10 years after arrival at its destination and will be accessible to a large number of scientific researchers on a scheduled basis in a manner similar to astronomy observatories.

(2) Global Services Systems

(a) Seasat Follow-On in low polar orbit will study geoid shape and sea surface to a high degree of precision.

(b) TIROS-O measures sea and air temperatures, wind velocities, and polar/sea ice movements.

(c) Soil Moisture Satellite measures global soil moisture conditions for crop prediction and irrigation planning.

(d) STORMSAT in geosynchronous orbit carries atmospheric sounders and imaging radiometers and will monitor and predict severe storms.

(e) Global Communications is a system of communication satellites including large antennas for electronic mail, TV, etc.

(f) Global Crop Forecasting is a system of high-data-rate satellites to determine world crop status and provide biweekly production forecasts.

(g) High Resolution Sea Survey is a system of satellites to survey and forecast sea conditions and sea resources.

(h) Disaster Warning is a system of satellites for detecting and predicting hazards (e.g., forest fires, tornados, insect infestations, etc.).

(i) Earth Energy Budget Monitor is a system of satellites to measure total solar flux and radiation received on Earth.

(j) Large Scale All-Weather Survey is a system of satellites to provide global measurements of temperature, humidity, winds, clouds, etc.

(k) Geological Mapping is a system of satellites for continuous updating of geological maps for ground resource exploration.

(l) Global Navigation is a system of large-structure (4 km) satellites with multibeam antennas and individual access.

(3) Utilization of Space Systems

(a) Space Manufacturing Modules produce biological and inorganic products for research and commercial use.

(b) Space Health Care System develops and provides onboard health care to passengers and crew of future manned missions.

(c) Lunar Precursor Processor uses solar energy to extract materials from lunar soil delivered by rovers to stockpile for lunar base.

(d) Nuclear Waste Disposal delivers nuclear wastes to low Earth orbit and then to a deep space destination.

(e) Teleoperator Vehicle System is a manned semiautomated vehicle with its own propulsion system and remotely controlled arms and is used for orbital construction and maintenance operations.

(f) Robot Vehicle for Earth Orbit is an unmanned automated vehicle with its own propulsion system and manipulators and is used for orbital operations.

(g) Lunar Base builds a lunar survey and precursor processor system and will perform mining, processing, and plant operations.

(h) Space Station is a large manned space structure. The space station can be equipped with auxiliary modules dedicated to commercial processing, a centralized data processing facility, liquid storage and transfer depot, and maintenance, repair, checkout, and general storage facilities.

(i) Satellite Power System is a large-scale ($\sim$100 km^2) space-based solar power generating, conversion, and transmission station located in geosynchronous orbit. The photovoltaic or solar thermal (Brayton cycle) generated power will be converted to microwave energy and beamed to a receiving rectenna on Earth.

(4) Transportation Systems

(a) Orbital Transfer Vehicle (OTV) transports large payloads in the space between low Earth orbit and geosynchronous orbit.

(b) High Energy OTV delivers large payloads to high-energy Earth escape missions (e.g., outer planets).

(c) Priority Launch Vehicle provides economical transportation to and from low Earth orbit for 15 to 100 tons per flight.

(d) Heavy-Lift Launch Vehicle is a low-cost, two-stage, fully recoverable automatic launch vehicle to low Earth orbit for 100-to 500-ton payloads.

The mission categories and years shown are based on those described in the NASA/OAST Space Systems Technology Model (Ref. 1). These missions are representative of those expected to be flown in the 1980s and 1990s. They are presented here only for the purpose of identifying critical functional and technological areas related to robotics and automation in that time frame.

The required technology development effort for each mission and functional area is qualitatively estimated with respect to the present state of technology and is shown to belong to one of the following five identified levels:

(1) Integration of Existing Technology - The technology is presently available but must be prepared and integrated into such a mission.

(2) Moderate Additional Developments - Moderate technology developments at the level of supporting research and technology would be required to take full advantage of existing capabilities. Generally, this could be accomplished after, or within about 1 year before, approval of such a mission.

(3) Extensive Technology Developments - The required technology needs approximately 5 years lead time. No technological innovations are required for mission success but can enhance effective mission operation.

(4) Major Technology Developments - The required technology needs approximately 10 years lead time. Innovations are highly desirable for effective mission operations.

(5) Major Technology Developments With Uncertain Outcome - The required technology needs approximately 15 years lead time. Innovations are required to enable the mission and/or to operate it with acceptable effectivity.

In those cases in which no adequate lead time is available, the particular function would be performed in a less cost-effective or qualitatively degraded manner; or a technical innovation would shorten the lead time. Another choice is to postpone the mission.

More detailed analyses with quantitative assessments of the required technologies are being conducted at JPL. Broadly speaking, the present state of applied space robot and automation technology is represented by the missions and activities listed in the Appendix. Reviewing a few mission categories will help show the trend of robot and automation technology and possible beneficial applications in the space program.

A. SPACE EXPLORATION

Space exploration robots may be exploring space from Earth orbit like orbiting telescopes, or they may be planetary flyby and/or orbiting spacecraft like the Mariner and Pioneer families. They may be stationary landers with or without manipulators like the Surveyor and the Viking spacecraft, or they may be wheeled like the Lunakhod and the proposed Mars rovers. Others may be penetrators, flyers, or balloons (Ref. 12), and some may bring science samples back to Earth (Figures 5-7). All have in common that they can acquire scientific and engineering data using their sensors, process the data with their computers, plan and make decisions, and send some of the data back to Earth. Some robots are in addition able to propel themselves safely to different places and to use actuators, manipulators, and tools to acquire samples, prepare them, and perform in situ experiments or bring them back to Earth.

Exploration robots are required to send back most of the collected scientific data, unless it becomes repetitive or is meaningless and can be discarded. The unknown space environment accessible to the sensors is translated into a different, still uninterpreted environment, in the form of computer data banks on Earth. These data banks are then accessible for scientific investigations long after the space mission is over.

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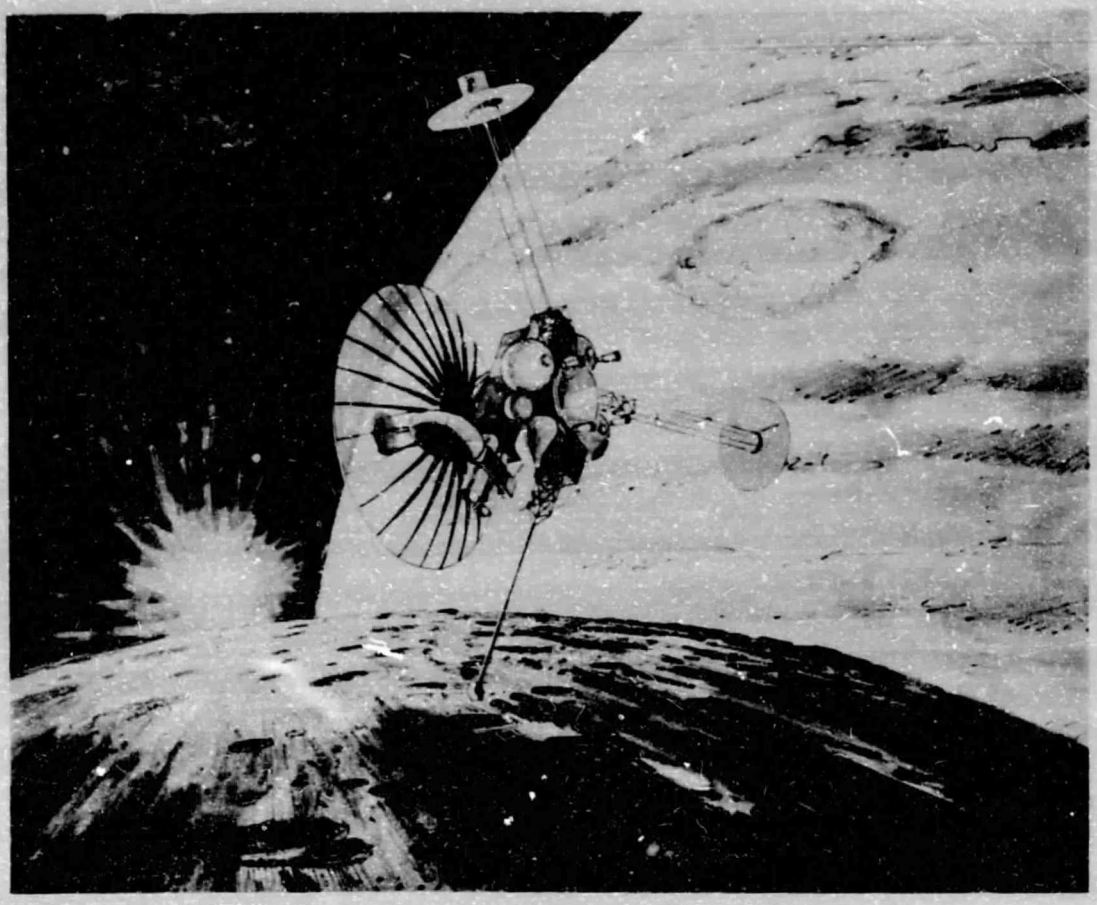

Figure 5. Galileo spacecraft navigates between Jupiter and Galilean satellites in rendering. After sending a probe into the Jovian atmosphere, the robot spacecraft will perform complex maneuvers at various orbital inclinations with repeated close encounters with the satellites.

As on-board data acquisition requirements and mission complexity increase, more data is sent to the ground that must be coordinated and handled. If mission durations also increase, the ground-based mission operations will quickly use up a major part of the total mission cost (Figure 8). With more capable on-board machine intelligence, the robot will be able to perform many of the ground-based operations in space autonomously (Figure 9). This would relieve ground activities and would greatly contribute to cost reductions for the same mission operations. Adapting advanced automation techniques to ground-based operations would also lead to significant cost savings (Figure 10). The combined effect of applying advanced automation technology to exploration missions is projected to yield a cost improvement of about two orders of magnitude by the year 2000 (Figure 11).

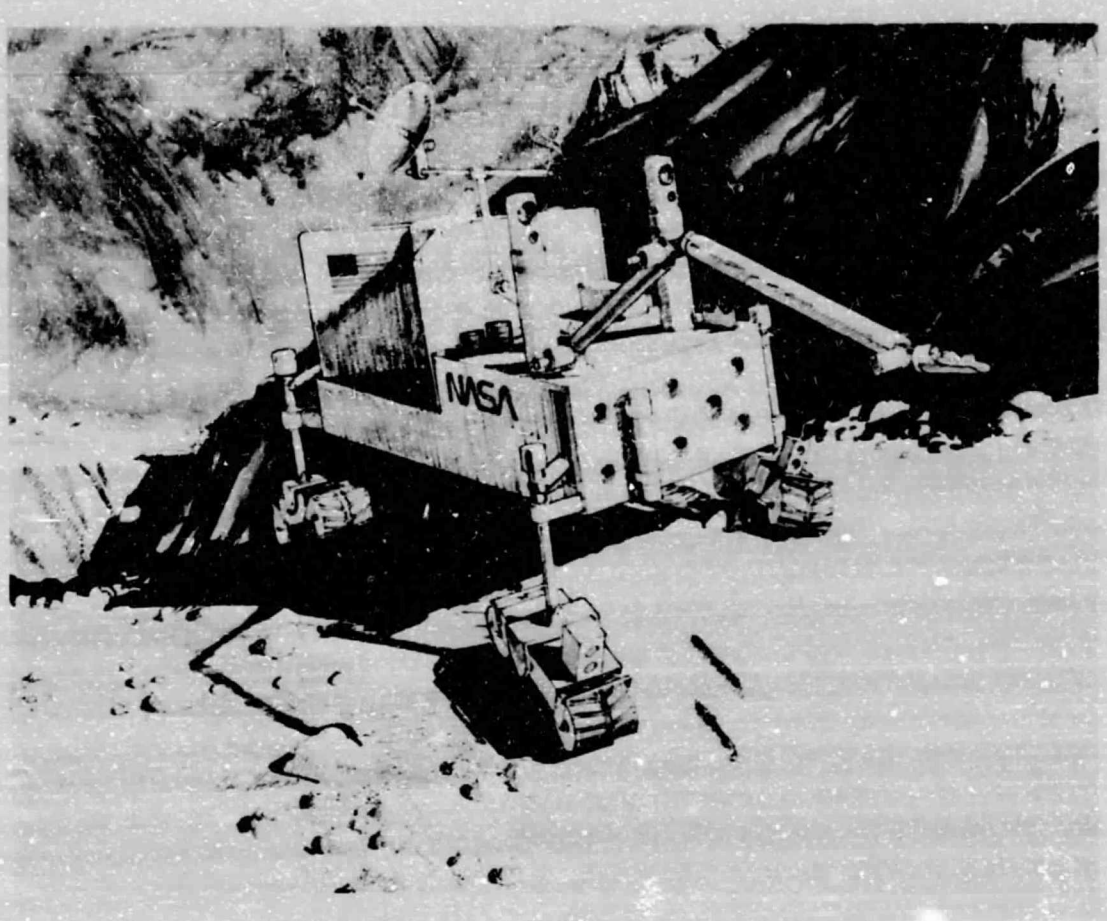

Figure 6. Mars surface robot will operate for 2 years and travel about 1000 km performing experiments automatically and sending the scientific information back to Earth.

A qualitative measure for the level of machine intelligence is the number of decisions made by the robot versus those made by its human supervisor. For a particular operation like "dig a trench," the total number of elementary decisions is presumably constant at approximately 1000. With increased machine intelligence capabilities, the robot will make a correspondingly increased number of the required decisions (Figure 12).

Projections into the future lead one to speculate on the possibility of highly autonomous exploration robots in space. Such exploration robots would communicate to Earth only when contacted or when a significant event occurs and requires immediate attention on Earth. Otherwise, they would collect the data, make appropriate selective decisions, archive it, and store it on board. They would serve as a data bank, and their computers would be remotely operated by accessing and programming them from Earth whenever the communication link to the

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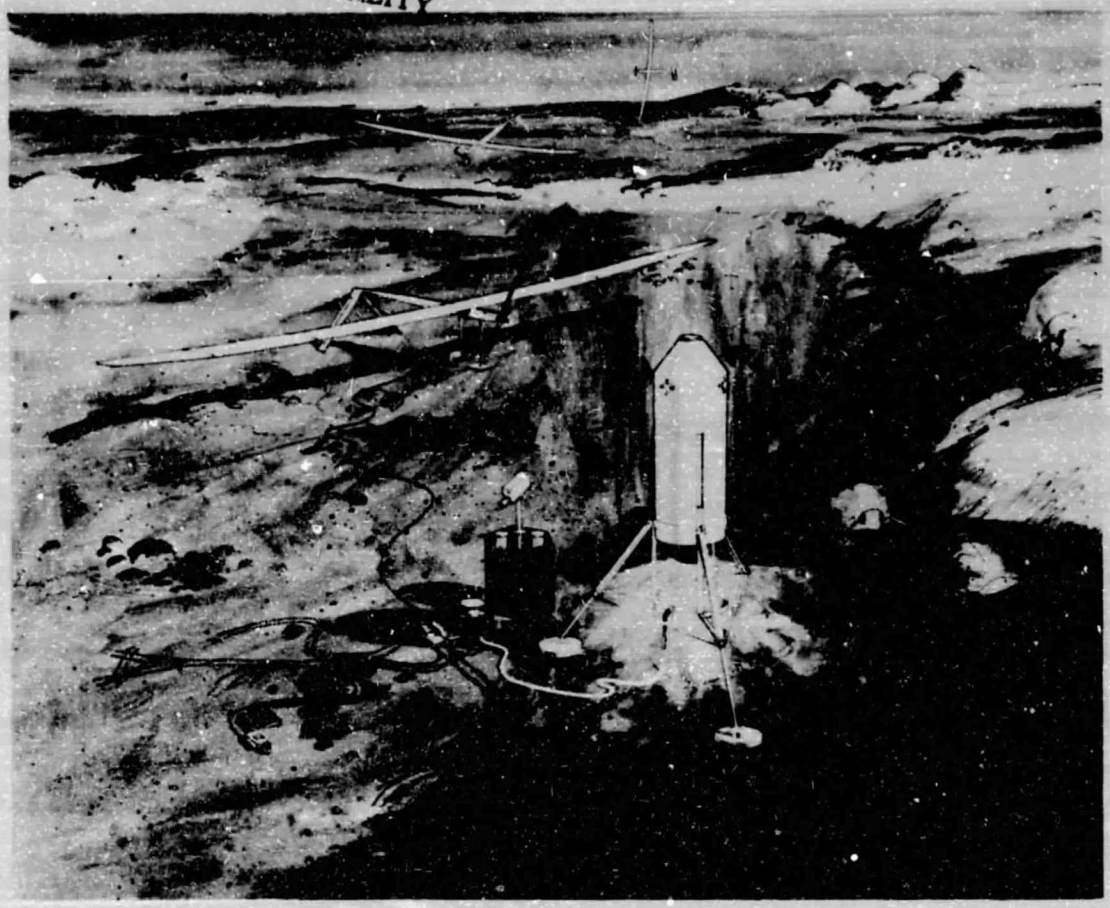

Figure 7. Artist's concept of a Mars surface scientific processing and sample return facility. Airplanes transport samples into the vicinity of the processing station. Tethered small rovers then bring the samples to the station for appropriate analysis and return to Earth.

robot spacecraft is open. Scientists would be able to interact with the robot by remote terminal. Indeed, the concept of distributed computer systems, presently under investigation in many places including JPL, could provide to each instrument its own microcomputer, and scientists could communicate with their respective instruments. They could perform special data processing on board and request the data to be communicated to them in the form desired. Alternatively, they could retrieve particular segments of raw data and perform the required manipulations in their own facilities on Earth.

Prime elements in the "scientist-deep space robot" link would be large antenna relay stations in geosynchronous orbit. These stations would also provide data handling and archiving services, especially for exploration robots which will not be accessible after a relatively short time, e.g., those leaving the solar system.

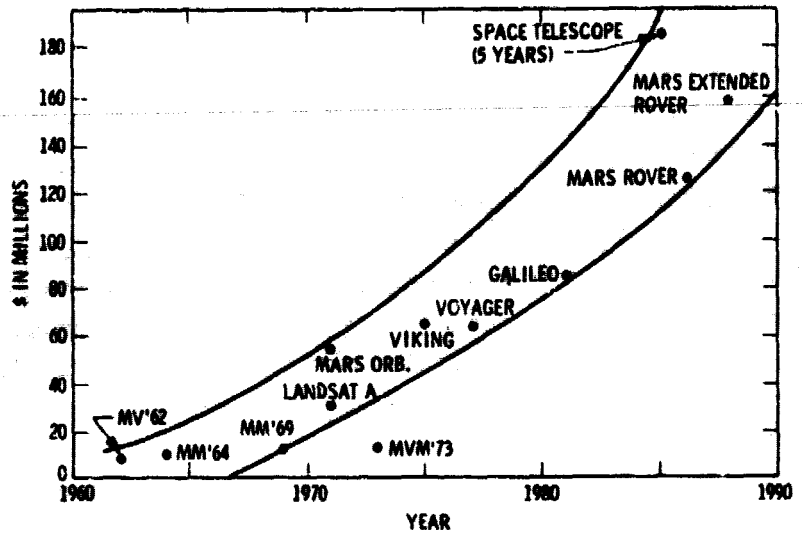

Figure 8. Trend of mission ground operation costs. Increasing mission complexity and duration contribute to the ground operation costs.

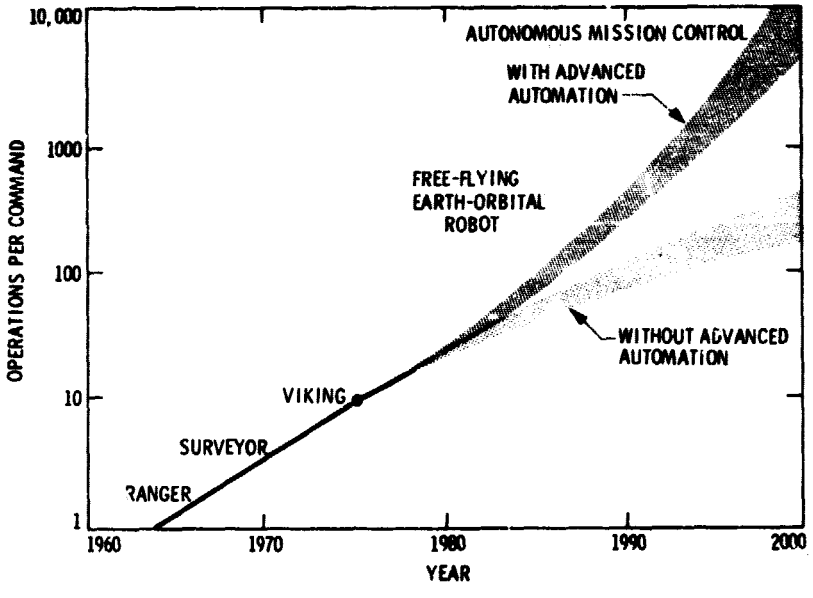

Figure 9. Trend of spacecraft automation. As a relative indicator, the level of automation is measured by the different elementary functions the spacecraft can perform in an unpredictable environment between ground commands. A 100-fold improvement through advanced automation is projected by the year 2000.

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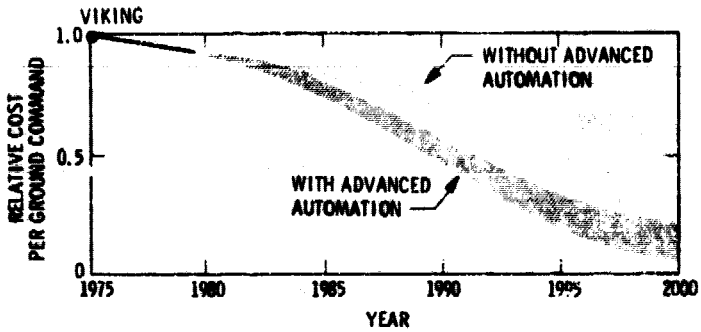

Figure 10. Trend of cost to generate ground commands. A four-fold improvement through advanced automation is projected by the year 2000 through (1) performing more ground functions on the spacecraft and (2) automating the remaining functions on the ground.

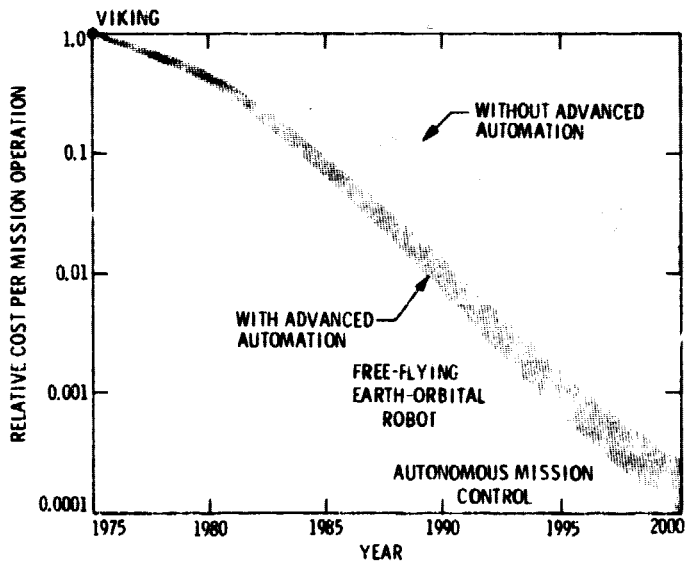

Figure 11. Trend of cost per mission operation. A 100 to 1000-fold improvement through advanced automation is projected by the year 2000 for executing a typical mission operation.

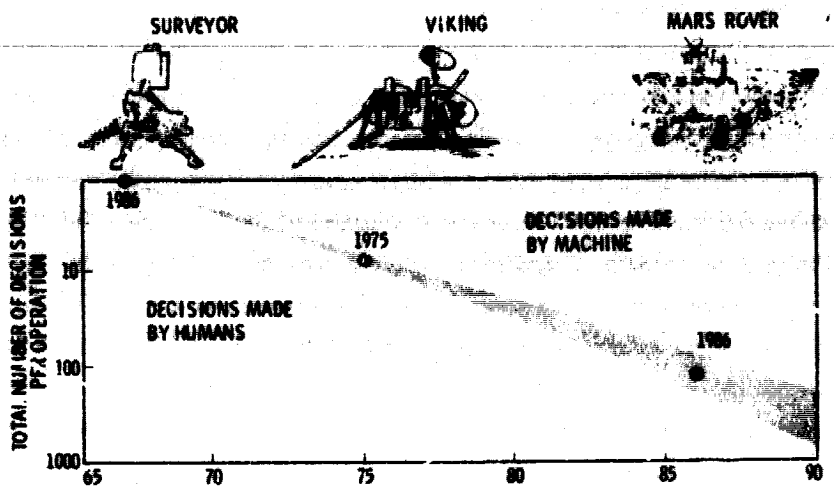

Figure 12. Trend of function (decision) allocation between humans and robots. For the same typical operation, the robot takes over an increasing number of elementary functions, leaving the high-level decisions to humans.

B. GLOBAL SERVICES

Global services robots orbit the Earth. They differ from exploration robots primarily in the intended use of the collected data. They collect data for public service use on soil conditions, sea states, global crop conditions, weather, geology, disasters, etc. These robots generally acquire and process an immense amount of data. However, only a fraction of the data is information of interest to the ultimate user. At the same time, the user often likes to have the information shortly after it has been obtained by the spacecraft. For instance, the value of weather information is short-lived except for possible historical reasons. The value of information on disasters such as forest fires is of even shorter duration. The demand for high-volume on-board data processing and pertinent automated information extraction is therefore great.

The usual purpose of global services robots is to collect time-dependent data in the Earth's environment, whose static properties are well known. The data is used to determine specific patterns or classes of characteristics and translate these into useful information. For instance, for LANDSAT and Seasat A (Figure 13), the data is presently sent to the ground, where it is processed, reduced, annotated, analyzed, and distributed to the user. This process requires up to 3 months for a fully processed satellite image and costs several thousand dollars. The image must then be interpreted by the receiver; i.e., the information must still be extracted by the user. Preliminary more advanced data system concepts for an operational Seasat system have been studied (Ref. 13).

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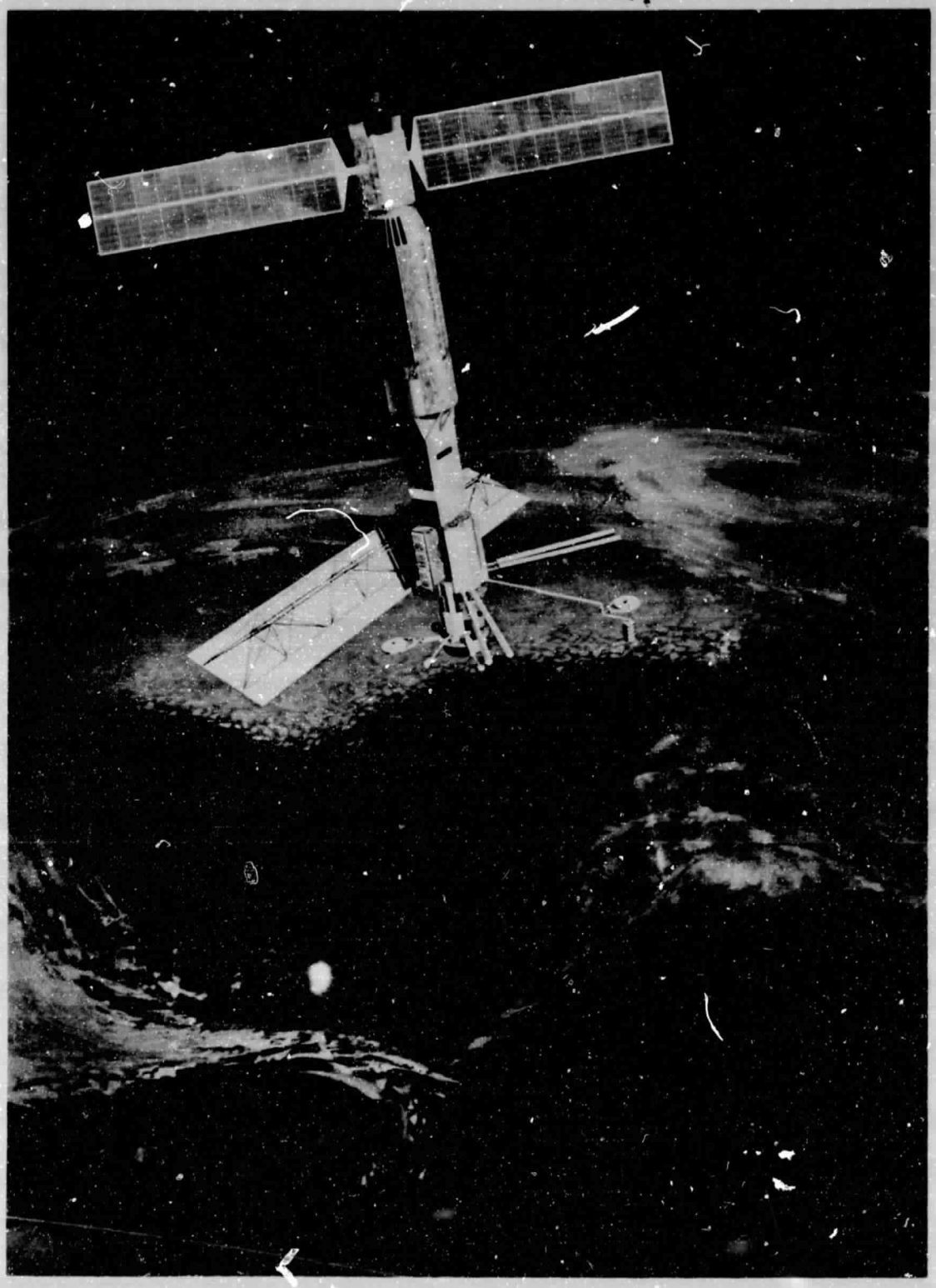

Figure 13. Seasat A over the Gulf of Alaska. The oceanographic satellite's high-data-rate Synthetic Aperture Radar imaging device will provide data on ocean waves, coastal regions, and sea ice.

Present developments in artificial intelligence, machine intelligence and robotics suggest that in the future, the ground-based data processing and information extraction functions will be performed on board the robot spacecraft. Only the useful information would be sent to the ground and distributed to the users, while most of the collected data could be discarded immediately. This would require the robot to be able to decide what data must be retained and how it was to be processed to provide the user with the desired information. For instance, the robot's computer brain could have a large number of pattern classification templates stored in its memory or introduced by a user with a particular purpose in mind. These templates would represent the characteristics of objects and/or features of interest. The computer would constantly compare the scanned patterns with those stored in its memory. As soon as something of interest appeared, it would "take a closer look" by zooming in on the pattern and examining it with higher resolution, comparing it to a progressively narrower class of templates until recognition had been established to a sufficient degree of confidence. The robot would then contact the appropriate ground station and report its findings and, if required, provide the user with an annotated printout or image. One can envision that the user would be able to interact with the robot, indeed with his particular instrument, by remote terminal much the same as with a central computer and, depending on intermediate results, modify subsequent processing.

For space exploration and global services, the ground-based mission operations can become an incredibly complex process. For planetary missions, these mission operations are handled primarily by the Deep Space Network and the Space Flight Operations Facility at JPL.

The latest example of a planetary exploration mission, and perhaps the most complex to date, is Viking. At times there were several hundred people involved in science data analysis, mission planning, spacecraft monitoring, command sequence generation, data archiving, data distribution, and simulation. While for earlier space missions sequencing had been determined in advance, on Viking this was done adaptively during the mission. The operational system was designed so that major changes in the mission needed to be defined about 16 days before the flight action. Minor changes could be made as late as 12 hours before sending a command. The turnaround time of about 16 days and the number of people involved contributes, of course, to sharply increased operational costs (Figure 8). The Viking operations costs are for a 3-month mission. The planned Mars surface rover mission is expected to last 2 years, covering many new sites on the Martian surface. Considering that this mission would be more complex and eight times as long, ground operations would have to be at least ten times as efficient to stay within, or close to, the same relative costs as for Viking.

During the Viking mission, about 75,000 reels of image data tapes were collected and stored in many separate locations. The images are now identifiable only by the time when and the location where they were taken. No indication regarding image information content is provided, and the user will have to scan catalogs of pictures to find what he wants. For such reasons, it is expected that most of the data will not be used again.

The ground operations for Earth orbital missions suffer from similar problems (Ref. 11) as those for planetary missions. The overall data stream is usually much higher here, images are still very costly, and they take up to several months to reach the user.

These considerations lead one to conclude that technology must be developed so that most ground operation activities can be performed as close as possible to the sensors where the data is collected, namely by the robot in space. However, examining the various ground operations in detail, it becomes clear that most of those that must remain on the ground could also be automated with advanced machine intelligence techniques. The expected benefits derived from this would be a cost reduction for ground operations of at least an order of magnitude and up to three orders of magnitude for user-ready image information.

C. UTILIZATION OF SPACE SYSTEMS

Space industrialization requires a broader spectrum of robotics and automation capabilities than those identified for space exploration and global services. The multitude of systems and widely varying activities envisioned in space until the end of this century will require the development of space robot and automation technology on a broad scale. It is here that robot and automation technology will have its greatest economic impact. The systems under consideration range from large antennas and processing and manufacturing stations in Earth orbit to lunar bases, to manned space stations, to satellite power systems of up to 100 km^2 (Refs. 14-28). These systems are not matched in size by anything on Earth. Their construction and subsequent maintenance will require technologies not yet in use for similar operations on Earth.

Space processing requires a sophisticated technology. First it must be developed and perfected, and then it must be transferred into the commercial arena. Basic types of processes presently envisioned are: solidification of melts without convection or sedimentation, processing of molten samples without containers, diffusion in liquids and vapors, and electrophoretic separation of biological substances. It is expected that specialized automated instrumentation will be developed for remote control once the particulars of these processes are worked out and the pressure of commercial requirements becomes noticeable.

Large-area systems such as large space antennas, satellite power systems, and space stations require large-scale and complex construction facilities in space. Relatively small systems, up to 100 m in extent, may be deployable and can be transported into orbit with one Shuttle load. For intermediate systems of several-hundred-meter extension, it becomes practical to shuttle the structural elements into space and assemble them on site (Figures 14-16).

Very large systems require heavy-lift launch vehicles which will bring bulk material to a construction platform (Figure 17), where the structural components are manufactured using specialized automated machines (Figure 18).

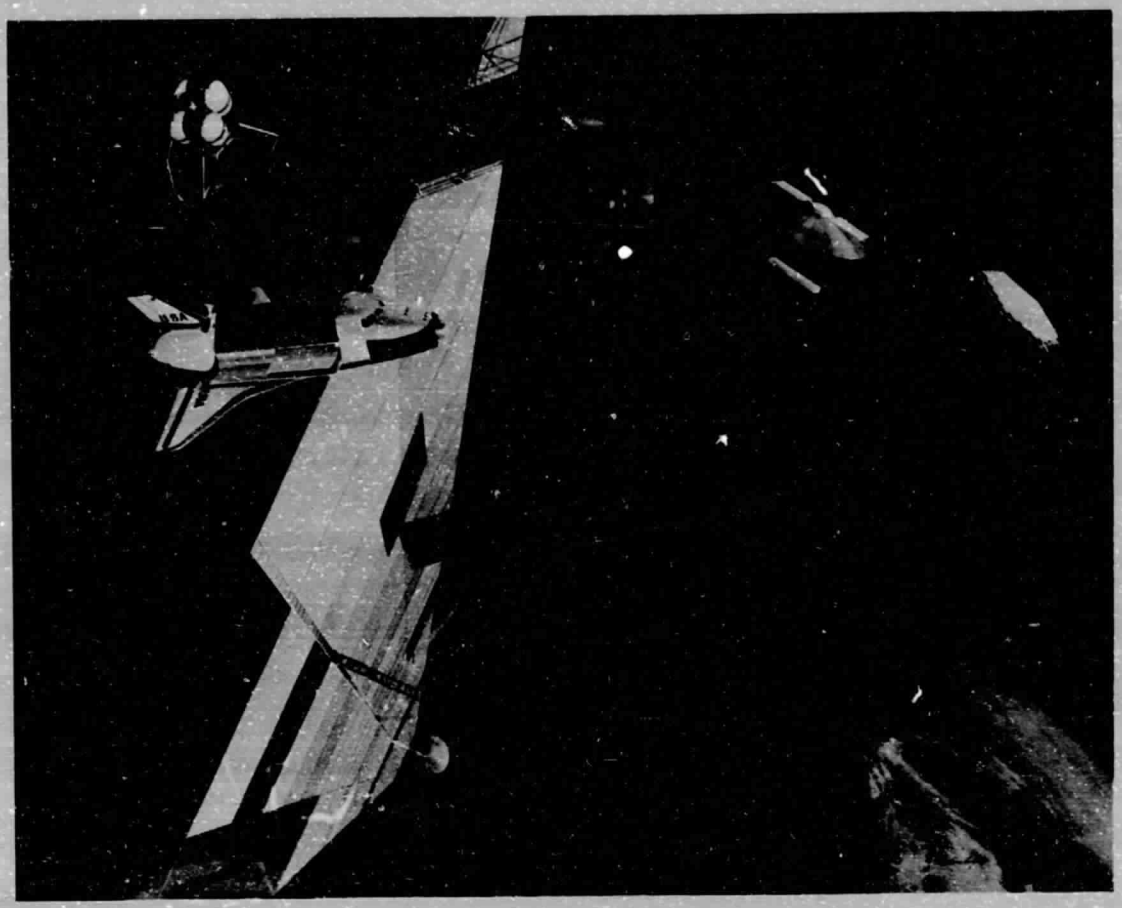

Figure 14. Large space systems require robot and automation technology for fabrication, assembly, and construction in space.

The structural elements will be handled by teleoperated or self-acting cranes and manipulators which bring the components into place and join them (Figure 19). Free-flying robots will transport the structural entities between the Shuttle or the fabrication site and their final destination and connect them. These operations require a sophisticated general-purpose handling capability. In addition to transporting structural elements, the robot must have manipulators to handle them, and work with them and on them. Large structural subsystems must be moved from place to place and attached to each other. This usually requires rendezvous, stationkeeping, and docking operations at several points simultaneously and with high precision -- a problem area still not investigated for zero gravity. Automated (smart) tools would also be required by astronauts to perform special local tasks.

These robot systems could be controlled remotely like teleoperator devices, or they could be under supervisory control with intermittent human operator involvement. Astronauts in space or human operators on

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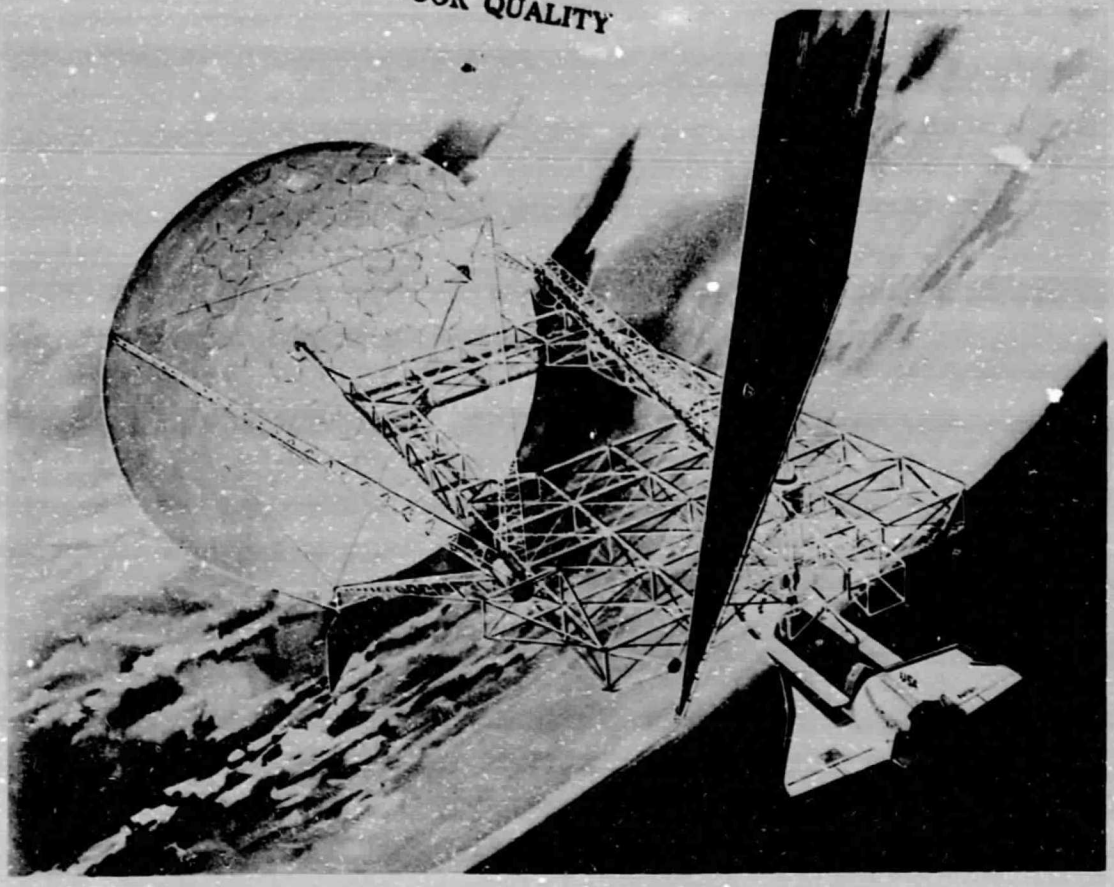

Figure 15. Large space antennas are erected with the help of a space-based construction platform. The Shuttle brings the structural elements to the platform, where automatic manipulator modules under remote control perform the assembly.

Earth will need the tools to accomplish the envisioned programs. The technology for in-space assembly and construction will provide the foundation for the development of these space-age tools.

After the system has been constructed, its subsequent operation will require service functions that should be performed by free-flying robots or by robots attached to the structure. The functions which such a robot should be able to perform include calibration, checkout, data retrieval, resupply, maintenance, repair, replacement of parts, cargo and crew transfer, and recovery of spacecraft.

During and after construction, there should be a robot on standby for rescue operations. An astronaut drifting into space could be brought back by a free-flying robot. Such devices could also be on

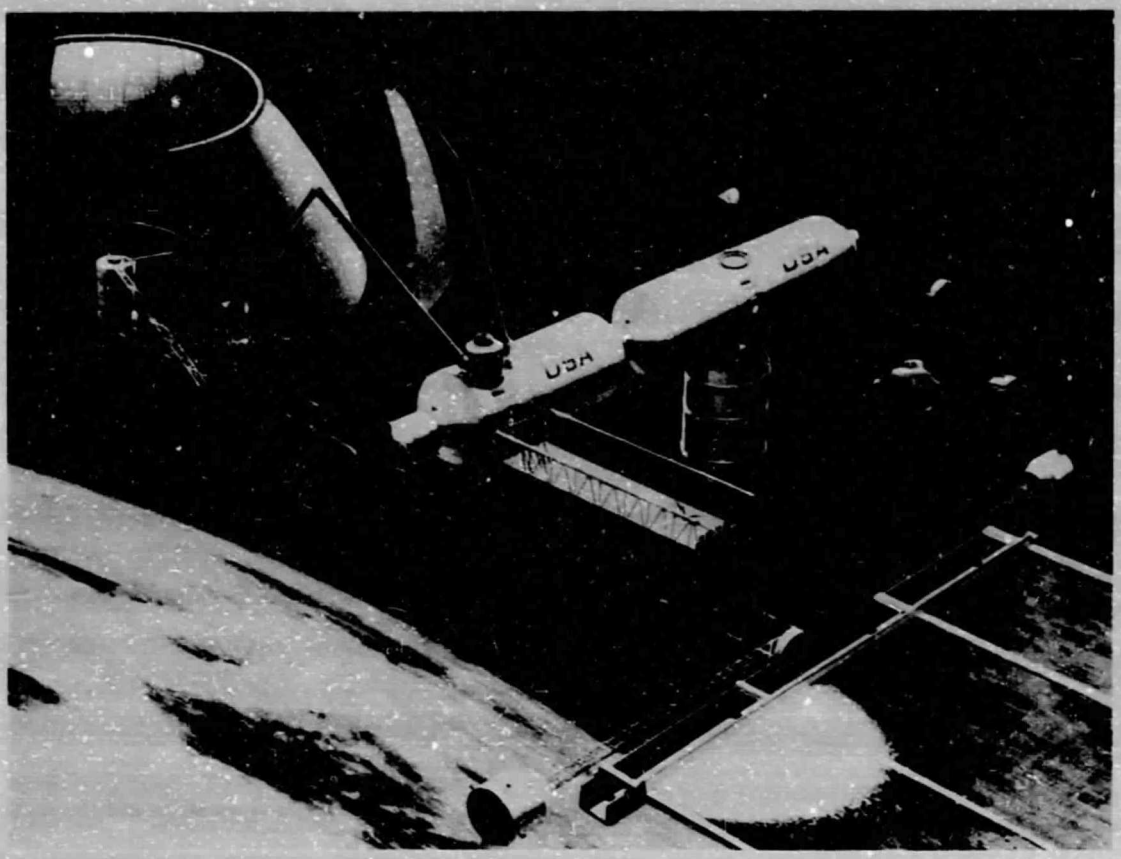

Figure 16. Construction of a space station. Bulk material is brought by the Shuttle. Structural elements are fabricated at the construction facility and then assembled by remotely controlled manipulators.

stand-by alert on the ground. The delivery systems for these rescue robots need not be man-rated. They can deliver expendable life support systems or encapsulate the astronaut in a life support environment for return to a shuttle, space station, or Earth. They could also perform first-aid functions.

Another phase of space industrialization calls for a lunar base. After a lunar surface survey with robot (rover) vehicles, an automated precursor processor system could be placed on the Moon. This system would collect solar energy and use it in experimental, automated physical/chemical processes for extracting volatiles, oxygen, metals, and glass from lunar soil delivered by automated rovers (Figure 20). The products would be stored, slowly building up stockpiles in preparation for a lunar base. The lunar base would be constructed using automated equipment and robots similarly as in Earth orbit. After construction, general-purpose robot devices would be necessary for maintenance and repair operations. In addition, the lunar base would use all types of industrial automation (qualified for operation in space) that is generally used on Earth for similar tasks.

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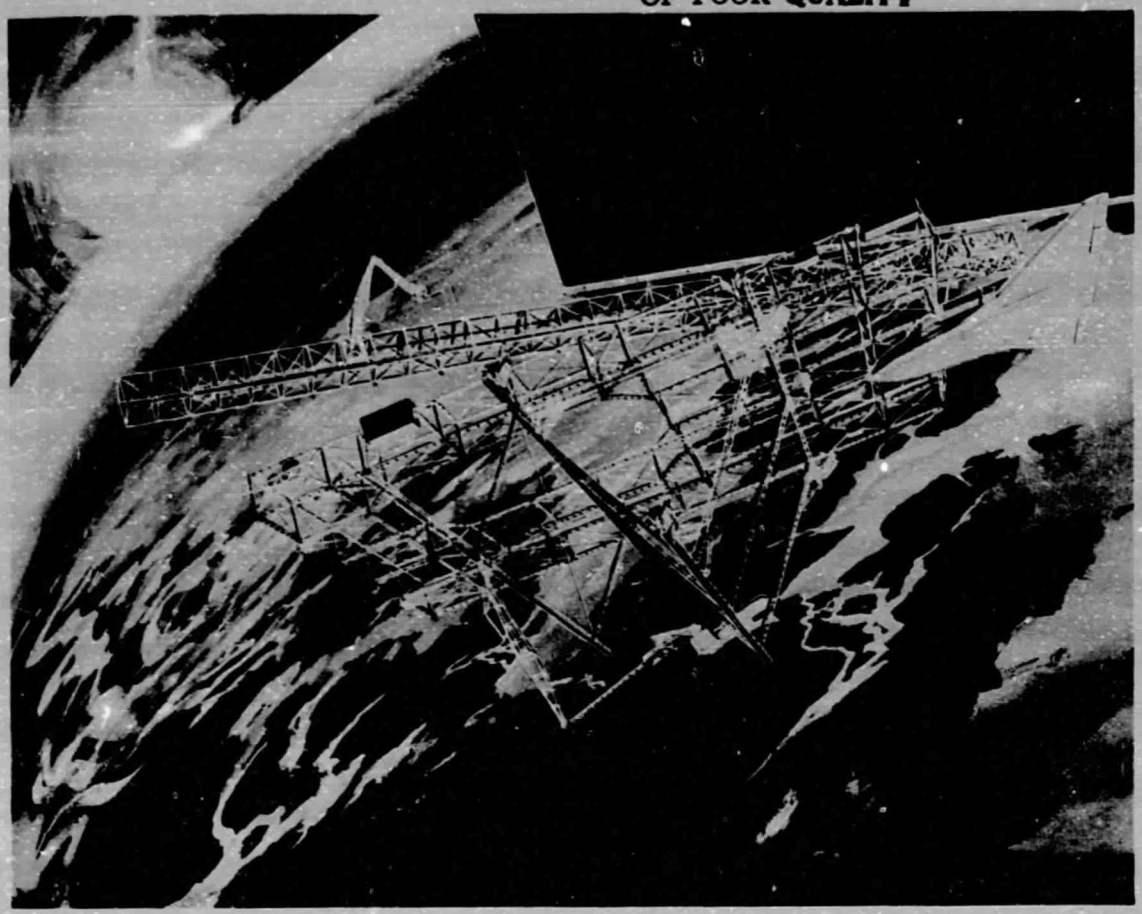

Figure 17. Complex construction facility in space with automatic beam builders, cranes, manipulators, etc., is served by the Shuttle.

In addition to acting as an enabling catalyst for some missions and reducing the cost of assembly and construction in space for others, the primary purpose of developing and applying robot and automation technology is the anticipated reduction of operation costs for all missions. It is therefore of interest to examine the NASA expenditures in various areas and to estimate potential cost savings, should an aggressive robot and automation research and development program be initiated. In a recent JPL study (Ref. 28), it has been estimated that about 600 million of the NASA budget in 1978 dollars could be saved annually by the year 2000 for ground operations, orbital operations, and data analysis. This does not include additional savings for incorporating advanced automation and machine intelligence techniques in design and testing operations. These projected savings also do not allow for the necessary expenditures to develop the required technology. Rough estimates for such investments range between 200 and 250 million in 1978 dollars to be spent on research and development between 1980 and

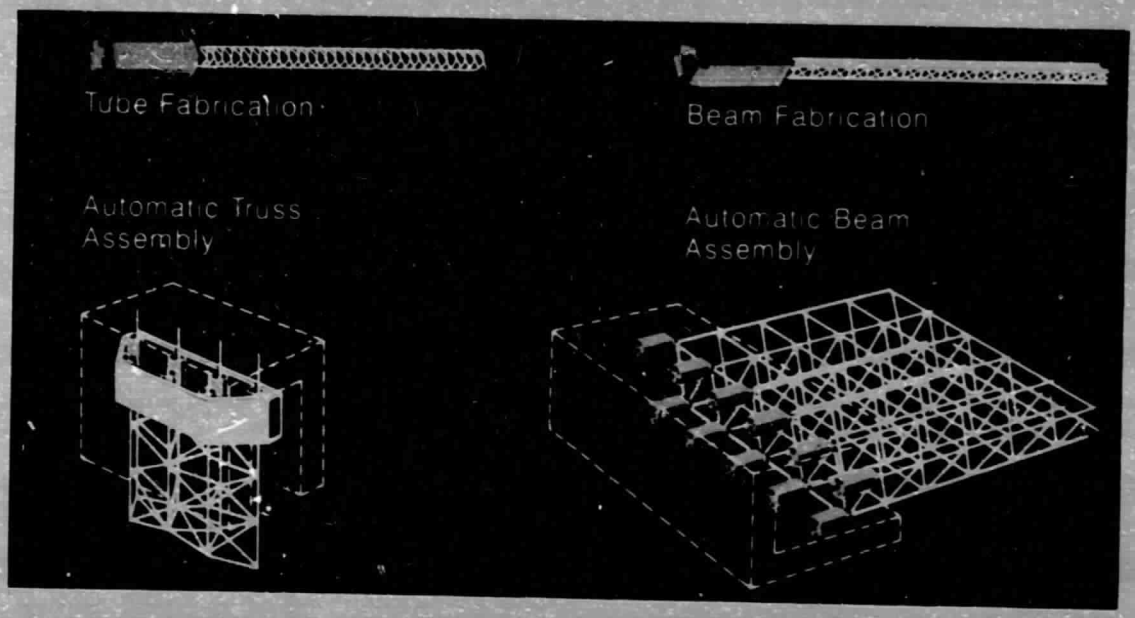

Figure 18. Automatic beam builders use sheet metal or bulk composite materials supplied by the Shuttle.

1995. This would be on the average about 0.4% of the NASA budget or about 12% of the OAST space budget. Although the estimated potential savings are subject to error, they indicate that space robot and automation technology is addressing high-leverage areas within the space program with large possible returns on the investment.

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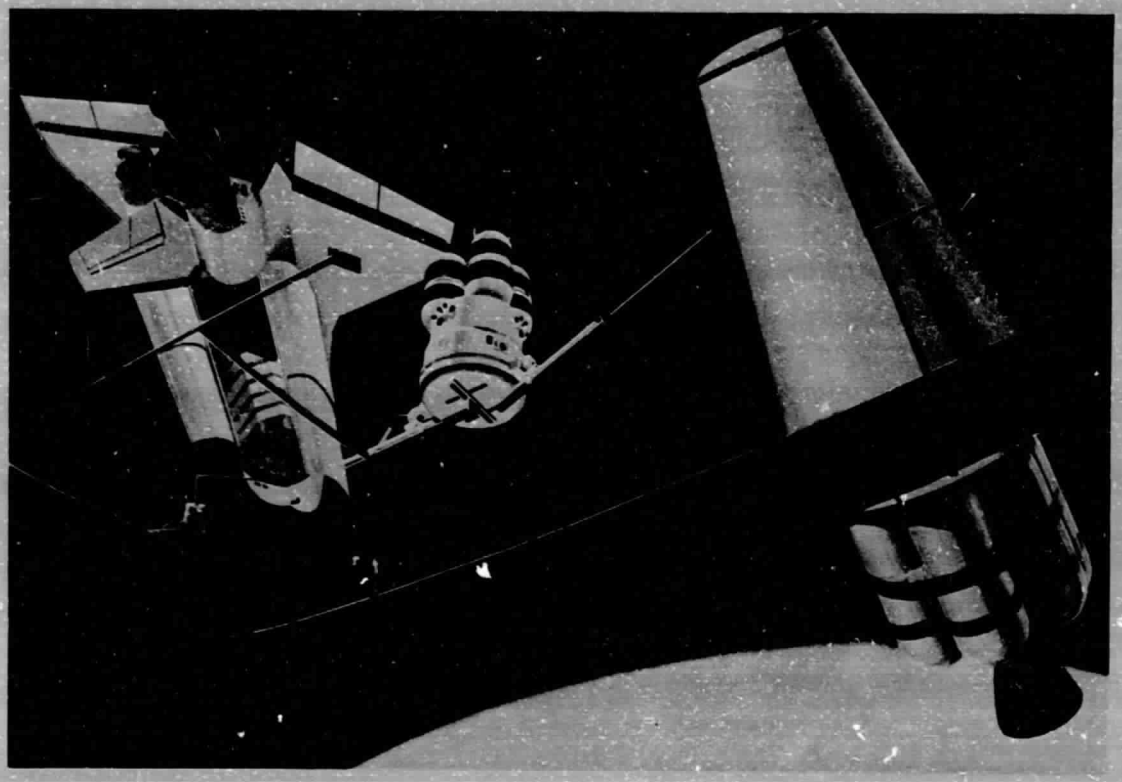

Figure 19. Space construction of large antenna systems with automated tools, teleoperated manipulators, and free-flying robots.

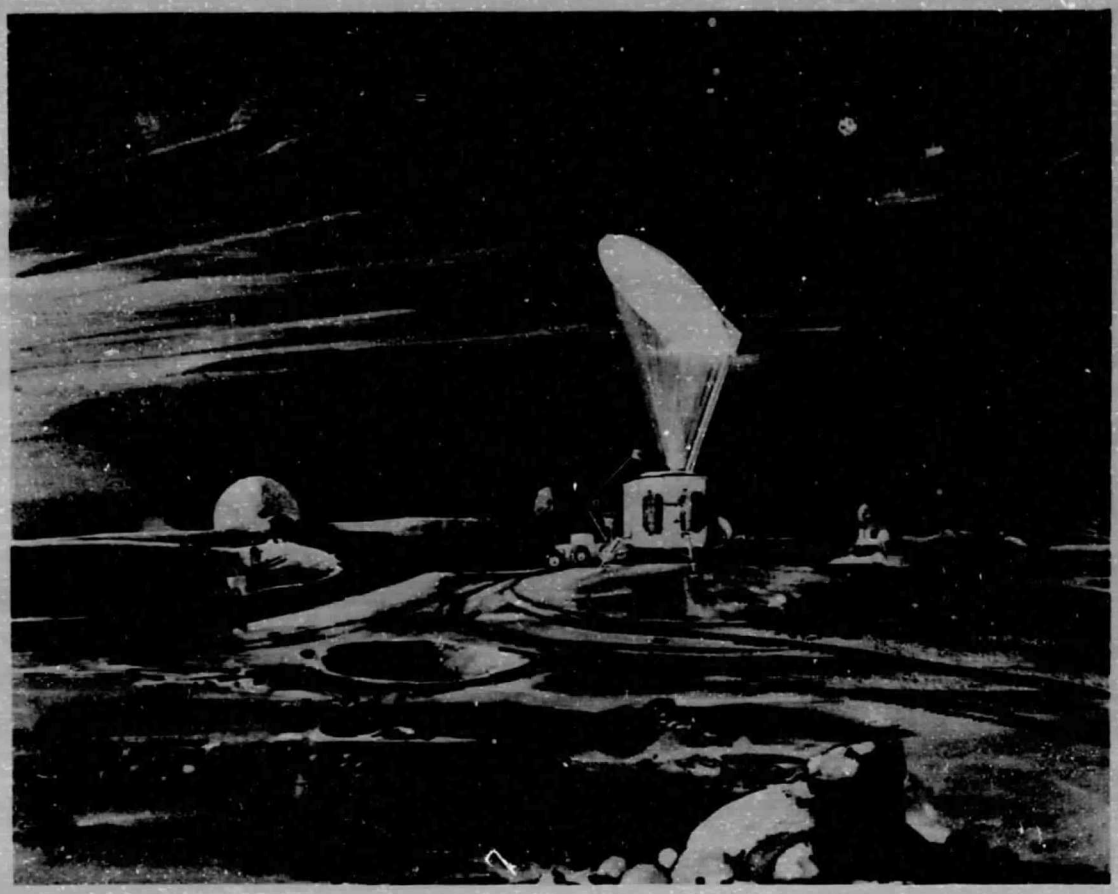

Figure 20. Automated material processors on the lunar surface are serviced by robot vehicles with raw lunar soil.

SECTION IV

SUMMARY

In summary, the space program is entering an era in which tremendous advances in sensor and computer technology offer great opportunities to introduce advanced autonomous operations leading to large cost savings and mission capability enhancements. The possibility of applying robot and automation technology exists in almost every activity within NASA. It is anticipated that the space program will also be pursued with vigor during the coming decades. It is therefore difficult to believe that the necessary tools will not be available and that the opportunities afforded by electronics technology will not be seized by NASA in order to develop the required robot and automation technology that will enable a more capable and cost-effective space program.

APPENDIX

HIGHLIGHTS OF SPACE ROBOT TECHNOLOGY

1967 - NASA SP-5047 (Ref. 2) presents the first comprehensive survey of teleoperator and robot technology to date. The development of teleoperator technology had its beginnings for serious, practical applications in the late 40s and early 50s, when it became necessary to control remotely located manipulators in hazardous environments of nuclear laboratories. With few exceptions, this work was done under the aegis of the Atomic Energy Commission. Nevertheless, in 1966, Case Institute of Technology, working under a NASA grant, demonstrated a computer-controlled manipulator that could perform preprogrammed tasks specified by the operator.

1967 - Surveyor III lands on the Moon. The claw and arm mechanism of the surface sampler gives the spacecraft the capability of a crude robot. Controlled remotely from Earth at each step, it digs trenches and performs soil experiments. Surveyor VII lands on the Moon in 1968 with the same remote operational capabilities as Surveyor III.

1968 - NASA SP-5070 (Ref. 3), a sequel to Ref. 2, reviews teleoperator and robot technology to that date with emphasis on controls.

1969 - NASA SP-5081 (Ref. 4) documents the proceedings of the colloquium on "Advancements in Teleoperator Systems" held at the University of Denver.

1970 - NASA conducts an inter-Center study on teleoperator/robot technology development requirements for the years 1970-1990 (Ref. 29). The study team recommends to the NASA Administrator a research and development program with focus on all subsystems (manipulators, mobility units, sensors, displays, controls, communications, artifical intelligence, etc.) and system integration.

1970 - Luna-16 lands on the Moon after performing remotely controlled orbital maneuvers. A drill extracts a sample and, under remote control, a "sample-return probe" brings the soil sample back to Earth. Luna-20 in 1972 and Luna-24 in 1976 repeat accomplishments of Luna-16.

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1970 - Luna-17 lands a remote-controlled wheeled rover (Lunakhod) on the Moon. Lunakhod slowly traverses several miles across the surface, taking pictures and probing the Moon with several scientific instruments. Luna-21 in 1972 repeats accomplishments of Luna-17.

1971 - NASA initiates a teleoperator and robot research program based on requirements (1) for the Space Shuttle attached manipulators at JSC, (2) for free-flying Earth orbital teleoperators at MSFC, and (3) for free-flying and extraterrestrial surface robots at JPL. A NASA-wide Committee for Remote Manipulator Systems and Extravehicular Activities is formed to guide the work and disseminate information about it.

1972 - NASA and the California Institute of Technology sponsor the "First National Conference on Remotely Manned Systems" devoted to the overall theme of Exploration and Operation in Space (Ref. 30). Forty-one papers cover free-flying teleoperators, Shuttle-attached manipulators, remote surface vehicles, manipulators, remote sensors and displays, man-machine interface systems, controls and machine intelligence, and nonspace applications.

1974 - NASA initiates a planning study, "Outlook for Space," to examine the civilian role of the U.S. space program during the following 25 years. Major advances in technology are forecast in microelectronics, automatic data processing, machine intelligence, large structural systems in space, space stations for large crews in space and on the Moon, and low-cost Earth-to-orbit transportation (Ref. 9).

1975 - NASA, California Institute of Technology, University of Southern California, J.S. Council for the Theory of Machines and Mechanisms, and Human Factors Society sponsor the "Second Conference on Remotely Manned Systems" devoted to the overall theme of Technology and Applications (Ref. 31). Forty-five papers cover theories and techniques, aerospace systems, undersea systems, industrial systems, and rehabilitation systems.

1975 - NASA/OAST Space Technology Workshop (Ref. 32) derives future technology requirements, major thrusts, and overall goals from the "Outlook for Space," and projects NASA mission and representative user needs.

The Workshop concludes that major advances are needed in autonomous operations, automated data processing, teleoperations, etc., for substantial increases in space system effectiveness.

1976 - Viking Mars Mission (two orbiters and landers) follows a series of planetary flyby and orbital missions during the past dozen years. The Viking lander is the most advanced space robot to date. Somewhat similar to the Surveyor spacecraft, it represents a much more capable technology. With a large degree of autonomous operation capability, it conducts long-duration, broad-scope scientific explorations. The on-board computer not only guides the lander safely to Mars' surface but also operates the lander for 58 Martian days without command from Earth (Ref. 33).

1976 - A Memorandum of Understanding between NASA and the Canadian National Research Council is signed. Canada will develop and deliver one Shuttle Remote Manipulator System to NASA by 1979 for flight testing in the Shuttle Orbiter Flight Test Program. The manipulator is remotely manually controlled but will be able to do simple transfer functions automatically.

1976 - NASA/OAST Space Theme Workshop applies technology projections to three broad mission themes (Ref. 10): Space Exploration - concerned with effective solar system exploration and with the search for extra-terrestrial intelligence; Global Services - concerned with worldwide remote sensing, data handling, and communication; and Space Industrialization - concerned with construction and manufacturing in space, space power platforms, and advanced transportation systems.

1977 - The NASA Robot Research Program at JPL accomplishes its first major goal to demonstrate an operational scenario for an integrated robot system. Based on a single command, the robot identifies obstacles in its way, plans and executes a path to a final destination avoiding the obstacles, and samples and retrieves an object of interest at the destination. The integrated system is a highly capable facility for advanced robot and automation research.

1977 - The NASA Teleoperator Research Program at MSFC has developed technology for a Teleoperator Retrieval System (TRS) to be launched in 1979 to boost or deorbit Skylab. The TRS is designed to incorporate more extended capabilities including manipulators, stereo vision, and on-board data processing at a later date.

1977 - Two Voyager spacecraft are launched to fly by Jupiter in 1979 and Saturn in 1980/81. Designed for more than 4 years of operational life, long-range communications, and precision navigation, the spacecraft have in-flight reprogramming capability to support science investigations. On-board computers will sequence on-board operations, adapting to differing data acquisition requirements at Jupiter and Saturn, and during other mission phases.

1978 - The NASA Study Group on Machine Intelligence and Robotics submits to NASA its recommendations, which were developed in five workshops during the past year. The objectives of the Study Group were to identify opportunities for application, to estimate benefits of successful adoption, and to recommend program options for development of machine intelligence and robot technology. (The Study Group's Final Report is in preparation.)

1978 - A NASA Inter-Center Ad-Hoc Group is formed for Automated Operations R&D Program Planning. The Group uses the projections of the NASA/OAST Space Theme Workshops, the state of research in the NASA robot/teleoperator programs, and the recommendations of the NASA Study Group on Machine Intelligence and Robotics as input.

1978 - Seasat-A, a proof-of-concept mission, is launched into Earth orbit with five instruments to assess the utility of the collected data to physical oceanography, climatology, meteorology, and marine technology. Some of the data is transmitted in real time when the satellite is within view of appropriately equipped receiving stations, while other data is first stored on on-board tape recorders. There are no other on-board robot or automatic capabilities.

1978 - The Viking Orbiter 2 Spacecraft accomplishes a first in JPL's mission operations. An on-board operational checkout process is designed on the ground and sent to the spacecraft computer command subsystem (CCS). Housekeeping data monitoring and command generation, previously done on the ground, is autonomously and successfully handled by the CCS on the spacecraft.